Polarimetry of the Type Ia Supernova SN 1996X.

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ABSTRACT

We present broad-band and spectropolarimetry of the Type Ia SN 1996X obtained on April 14, 1996 (UT), and broad-band polarimetry of SN 1996X on May 22, 1996 (UT), when the supernova was about a week before and 4 weeks after optical maximum, respectively. The Stokes parameters derived from the broad-band polarimetry are consistent with zero polarization. The spectropolarimetry, however, shows broad spectral features which are due intrinsically to an asymmetric supernova atmosphere. The spectral features in the flux spectrum and the polarization spectrum show correlations in the wavelength range from 4900 Å up to 5500 Å. The degree of this intrinsic component is low ($\sim 0.3\%$). Theoretical polarization spectra have been calculated. It is shown that the polarization spectra are governed by line blending. Consequently, for similar geometrical distortions, the residual polarization is smaller by about a factor of 2 to 3 compared to the less blended Type II atmosphere, making it intrinsically harder to detect asphericities in SNIa. Comparison with theoretical model polarization spectra shows a resemblance to the observations. Taken literally, this implies an asphericity of ≈ 11 % in the chemical distribution in the region of partial burning. This may not imperil the use of Type Ia supernovae as standard candles for distance determination, but nontheless poses a source of uncertainty. SN 1996X is the first Type Ia supernova for which spectropolarimetry revealed a polarized component intrinsic to the supernova and the first Type Ia with spectropolarimetry well prior to optical maximum.

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1. Introduction

Polarimetry is a powerful way of probing asymmetries in supernova explosions. Because polarization produced within the supernova atmosphere may have spectral features that are distinguishable from the featureless interstellar polarization (ISP), which is caused by dust within both the Galaxy and the host galaxy, spectropolarimetry is usually a more powerful tool than broad-band polarimetry in decomposing the intrinsic polarization of a distant supernova from ISP.

SN 1987A and SN 1993J are the only two supernovae for which spectropolarimetry has been published and intrinsic polarizations are positively detected. SN 1987A is so far the best observed supernova for which linear polarimetry was obtained from several days to about 260 days after explosion (Mendez et al. 1988; Cropper et al. 1988; Jeffery 1991a). The degree of polarization evolved with time, indicating that the cause of the polarization is related intrinsically to SN 1987A. The data were analyzed (Höflich 1987; Jeffery 1991b) in terms of the photospheric scattering model (Brown & McLean 1977; Shapiro & Sutherland 1982). Recently, Wang & Wheeler (1996a) provided a different view in which time delayed scattering by a hypothesized circumstellar dust clump successfully reproduced both the broad-band and spectropolarimetry of the supernova and the early infrared light curve of SN 1987A (Bouchet et al. 1989). Linear polarization indicated by polarization changes across spectral features was also detected in SN 1993J (Trammell, Hines, & Wheeler 1993). Broad band polarimetry shows also variable polarization before and after the second optical maximum of SN 1993J (Doroshenko, Efimov, & Shakhovskoi 1995).

Only two Type Ia supernovae – SN 1983G (McCall et al. 1984) and SN 1992A (Spyromilio & Bailey 1992) have been previously observed by spectropolarimetry. The noise levels of the SN 1983G and SN 1992A data are 0.5% and 0.3%, respectively. These data indicate SN 1983G and SN 1992A are not polarized at a level higher than 0.5%.

As part of our program of systematic supernova polarimetry, we have observed 5 supernovae with broad-band polarimetry and compiled a catalog of all the supernovae with polarimetry reported in the literature (Wang et al. 1996). This sample shows that all the Type II supernovae with sufficient data are intrinsically polarized while no intrinsic polarization can be established for any of the Type Ia supernovae.

Supernovae, of both Type Ia and II, are now being widely used as standard candles for distance determinations. As a self-consistency test, it is imperative to set some observational constraints on the degree of the polarization. Furthermore, normal spectroscopy provides only part of the information carried by the supernova light. Spectropolarimetry can further constrain various models for spectral line formation and radiative transfer through supernova atmospheres, as shown in recent examples by Höflich (1995a), Höflich et al. (1996), and Höflich, Wheeler, & Wang (1997). Furthermore, it may be the only way to detect chemical blobs in the ejecta which usually produce little observable effects on the flux spectra of a supernova (Höflich, Wheeler, & Wang 1997).

2. The Observations

SN 1996X in NGC 5061 was discovered independently by several observers (Garradd 1996) on April 12.5 UT at a V magnitude about 13.5. Spectroscopy on April 14 UT showed SN 1996X to be a Type Ia supernova prior to optical maximum (Suntzeff 1996; Wang and Wheeler 1996b; Benetti and Patat 1996). Our spectropolarimetry of SN 1996X was obtained on April 14.3 using the Imaging Grism Polarimeter (IGP) mounted at the Cassegrain focus of the 2.1 meter telescope of the McDonald Observatory. The IGP is a simple, high efficiency, dual beam polarimeter which can be easily switched between imaging and spectropolarimetry mode. A rotatable half waveplate was used as the polarization analyzer. A description of the instrument can be found in Hill & Trammell (1996) and Trammell (1994). A TK4 (1024×1024) CCD was used as the detector. A broad filter with pass band from 4400 to 7500 was used for the broad-band polarimetry. Such a filter effectively filters out photons with wavelengths beyond the effective range of the waveplate, but allows a large number of photons to be transmitted for polarimetry. The slit width used for the spectropolarimetry was $2''.1$ which gave a spectral resolution of about 14Å. Wavelength calibration was obtained by taking exposures of an argon lamp.

The data were taken with clear and dark sky. Several unpolarized and polarized standard stars were observed each night. The data reduction process is the same as outlined in Miller, Robinson, & Goodrich

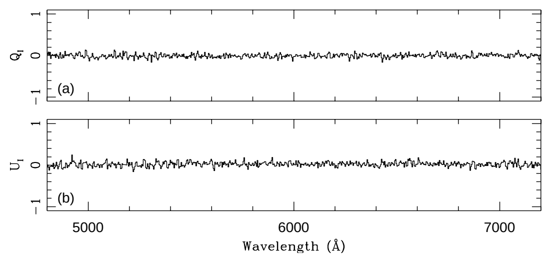

Fig. 1.— Instrumental polarization from observations of unpolarized standard stars.

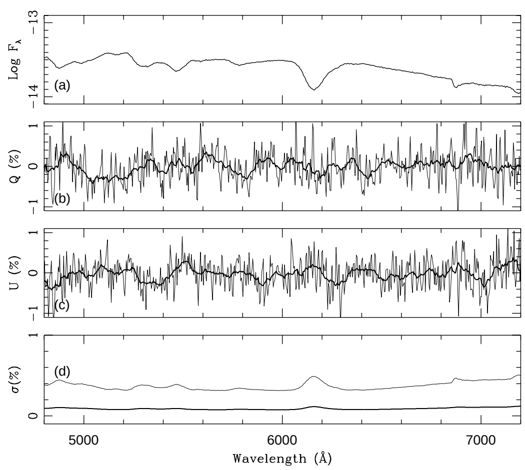

Fig. 2.— (a) The flux spectra of SN 1996X on April 14.3, 1996 UT in arbitrary units; (b) the Stokes parameter Q; (c) the Stokes parameter U; (d) the noise level of the Stokes parameters. In (b) - (c), the thin lines are the observed data at the original sampling step of 3.8Å/pixel, the thick lines are the same data resampled with a sample window width of 64.8Å(17 pixels).

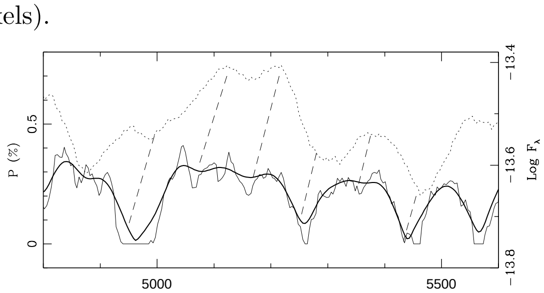

Fig. 3.— The wavelength range showing correlations between the flux spectrum (dotted line), the polarization spectrum from the resampled data (thin solid line), and the polarization of the data smoothed by convolving with a Gaussian of FWHM of 64.8Å(thick solid line).

(1988). The instrumental polarization obtained by observing several unpolarized standards is shown in Figure 1 (a) and 1 (b) and is found to be less than 0.1% in the entire wavelength range. The polarized standards were used to calibrate the polarization angles. In addition, observations were also obtained by inserting a polarizer at the top of the waveplate to characterize the efficiency of the waveplate and the wavelength dependence of the fast axis of the waveplate. The polarization efficiency is typically 95% at around 6500 Å and decreases to about 90% at 4500 Å. The variation of the fast axis with wavelength is less than 2°. These effects and also the instrumental polarization were taken into account and corrected for in the data that will be presented below.

3. Data and Results

Although the exact phase of the supernova awaits the publication of an accurate light curve, the supernova was at pre-maximum phase on April 14, as indicated by the flux spectrum shown in Figure 2 (a). The continuum was very blue and the Fe II lines were still not fully developed. The Stokes parameters Q and U derived from the spectropolarimetry are shown in Figures 2 (b) and 2 (c), and their errors in Figure 2 (d). The dominant error in Q and U was from photon statistics, and was the largest in the red portion of the spectra where it reached 1%; typical errors were less than 0.6% in regions around 5500 Å.

Polarizations higher than 1% can be reliably excluded from the Q and U spectra shown in Figure 2. However, at a lower level of about 0.3%, some broad features are present. For a simple test, the Q and U spectra were convolved with a Gaussian of FWHM of 65 Å. As shown in Figure 3, in the wavelength range from 4900 to 5500 Å, there exists a correlation between the wavelengths of these broad features and the spectral features in the flux spectrum.

To investigate the authenticity of this polarization variation with wavelength, the data were resampled to increase the signal to noise ratio. This was done by deriving the Stokes parameters within a certain wavelength window $\Delta\lambda$ centered on a particular wavelength, λ. This is equivalent to calculating the following weighted mean of the original Stokes parameters:

$$Q(\lambda|\Delta\lambda) = \int_{\lambda-\Delta\lambda/2}^{\lambda+\Delta\lambda/2} N(\lambda')Q(\lambda-\lambda')d\lambda' / \int_{\lambda-\Delta\lambda/2}^{\lambda+\Delta\lambda/2} N(\lambda')d\lambda', \tag{1}$$

where N is the number of counts per wavelength

interval. The corresponding equation for U can be similarly derived. Such an operation increases the signal to noise ratio of the data, but at the expenses of degrading the spectral resolution. Fortunately, the spectral features in a supernova spectrum are in general as broad as 150 Å, and useful information can still be obtained even if the resolution is as low as 100 Å. The Stokes parameters with an integration window of width $2 \times \Delta\lambda = 64.8$ Å are shown in Figure 2 (b) and (c). The noise level (σ) which is also shown in Figure 2 (d), is now typically around 0.1%.

The degree of polarization P can be constructed from the Stokes parameters Q and U. However, it is well known that for relatively high noise level, $P = \sqrt{Q^2 + U^2}$ is biased toward values larger than the true degree of polarization P_o ; P is usually not the best estimate of P_o . The distribution function for (P, θ) takes the form (Simmons & Stewart 1985)

$$f(P,\theta) = \frac{P}{2\pi\sigma}\exp\{-\frac{1}{2}[(\frac{P}{\sigma})^2+(\frac{P_o}{\sigma})^2-\frac{P}{\sigma}\frac{P_o}{\sigma}\cos(\theta-\theta_o)]\}, \tag{2}$$

where (P_o, θ_o) stands for the true degree of polarization and polarization position angle. Simmons & Stewart (1985) constructed optimal estimates of degree and position angle of polarization (P_o and θ_o) from the marginal distribution of polarization obtained by integrating over θ in equation (2). This method, however, does not usually simultaneously optimize P_o and θ_o. A simpler method can be constructed by requiring the best estimate of (P_o, θ_o) to take the values for which (P, θ) gives the maximum of the distribution $f(P, \theta)$. It is easy to derive from equation (2) that this results in the following simple formula for P_o and θ_o

$$\begin{array}{lll} P_o & = P - \sigma^2/P & P \geq \sigma \\ P_o & = 0 & P < \sigma \\ \theta_o & = \theta & \end{array} \tag{3}$$

Both the polarization P_o derived from equation (3) and P are shown in Figure 4(a). They differ mainly in wavelength regions with low signal to noise ratios. The polarization position angles could not be reliably determined for data with large errors, therefore only position angles calculated from the resampled Q and U are shown (Figure 4(b)).

An enlarged version of the part of the spectrum with strong correlations between the spectral features in the polarimetry and flux spectrum is shown in Figure 3, where the features are marked by dashed lines for illustrative purposes. The corresponding spectral features in the polarization spectrum which are correlated with the spectral lines in the flux spectrum are blue shifted by about 2200 km s^{-1}. No strong correlation between the flux and polarization spectra could be established at wavelengths longer than 6000 Å. This may be due to some intrinsic characteristics of the polarization of Type Ia SN (see §4 for a more detailed discussion). The position angles change across spectral features. This should not be a surprise when compared with the best observed supernova, SN 1987A, where the intrinsic component shows dramatic variations of both degree and polarization position angle across spectral features (Cropper et al. 1988).

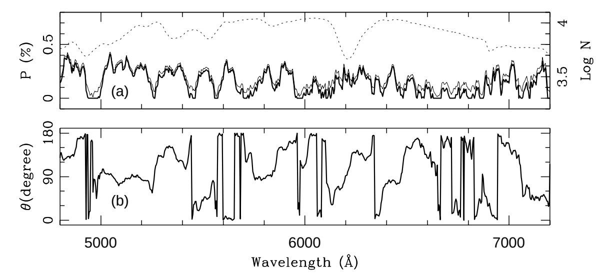

Fig. 4.— (a) The number of counts in a single beam of a 20 minute exposure on a logarithmic scale (dotted line); the degree of polarization resampled with a sample window width of 64.8Å; the degree of polarization P_o as defined in equation (2) (thick solid line). (b) The polarization position angle of the resampled data.

It is impossible to accurately correct for the effect of ISP. The Galactic extinction to the host galaxy NGC 5061 is $A_B = 0.25$, which alone can produce polarizations as large as 0.7% according to the limit derived by Serkowski (1970). The ISP correction is even more complicated by the polarization due to dust in the host galaxy; however, the ISP follows Serkowski's law, and is a smooth function of wavelength; the uncertainties introduced by the ISP will not change the Q and U spectral structures on wavelength scales less than a few hundred Å. The ISP correction can, however, dramatically change the appearance of the polarization spectra. The spectral features in Figure 4(a) may change from 'emission' to 'absorption' even if a very small amount of ISP correction $\sim 0.2\%$ is required. This should be borne in mind when interpretating the polarization spectra.

In addition to the spectropolarimetry discussed

above, we have also obtained broad-band polarimetry using a wide filter with pass band from 4000 − 7500 Å. Three and five data sets were obtained on April 14 and May 22, respectively. Each data set consists of four 100 second exposures which gave estimates of the Stokes parameters. The measured Q and U are practically zero for all data sets. The averaged values are $Q = 0.079 \pm 0.041\%$ and $U = 0.056 \pm 0.039\%$ on April 14, and $Q = 0.090 \pm 0.021\%$ and $U = 0.063 \pm 0.019\%$ on May 22, where the errors are due to photon statistics. The systematic instrumental uncertainty is around 0.06% (as indicated by repeated observations of unpolarized standards) and is therefore the dominant error for the broad-band data. The broad-band data are consistent with zero polarization. We do not confirm the short-term temporal variations of polarization reported in early polarimetry of another Type Ia SN 1972E (Lee, Wamsteker, & Wisniewski 1972, quoting observations made by Serkowski and Wamsteker).

It should be pointed out that the null detection in broad-band polarimetry did not conflict with the spectral features detected in the spectropolarimetry data. As a check for consistency, we have weighted the spectropolarimetry data with the transmission curve of the filter and the photon counts at different wavelengths to simulate broad-band polarimetry. The resulting Q and U are in agreement with the broad-band polarimetry data.

4. Models

Besides the attempt to identify features of the polarization with those of the flux spectrum, a more direct approach is a comparison with theory which provides additional information on the spectral patterns to be expected. A simplified approach is suitable to answer the following questions: what does the polarization spectrum look like for a SN Ia, what asphericity is needed to be consistent with the observation of SN1996X, and how do the predicted spectra compare with the observations ? Delayed detonation models (Khokhlov 1991) have been found to provide a good representation of the observed light curves and spectra of normal bright SN Ia (Höflich 1995b, Höflich & Khokhlov 1996 and references therein) and we use such a model to produce a representative theoretical SN Ia polarization. The polarization spectrum is given by Monte Carlo calculations based on the following assumptions: a) homologously expanding, ellipsoidal envelopes with density and chemical profiles given by a hydrodynamical model, b) occupation numbers given by local thermodynamical equilibrium (LTE); c) electron scattering, bound-free and free-free for continuum opacities; d) lines treated in a Sobolev approximation with an assumed constant thermalization fraction; e) line transitions result in depolarization; f) the temperature structure is given; g) and elliptical geometry with a axis ratio being independent of radius. Note that discrepancies between predicted and observed wavelengths of polarization features corresponding to 1000 to 2000 $\mathrm{km\,s^{-1}}$ may be expected because this difference is well within the observed variation of expansion velocities among normal bright SNe Ia. Lines of the same ion must, nevertheless, be expected to be shifted consistently. For more details, see Höflich et al. (1995).

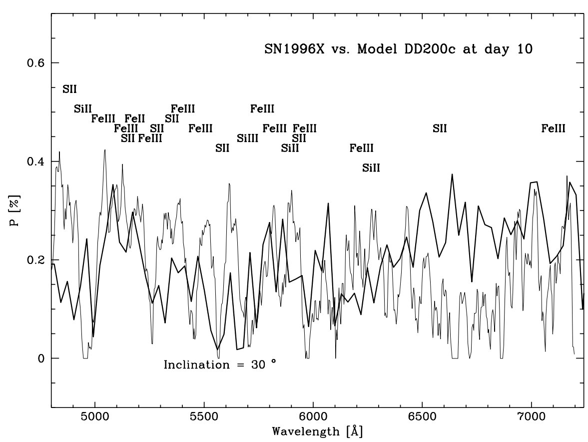

Fig. 5.— Comparison of the theoretical polarization spectrum of the delayed detonatinon model DD200c five days before maximum light (thick line; Höflich et al. 1996; axis ratio 0.88 seen at an inclination of 30°) with the observations (thin line). The identification of some features are given. Most of the weaker features are due to iron group elements in the second and third ionization stage. The S II and Si II features at about 4900, 5300, 5600 and 5670 Å are too strong and the overall polarization above 6500 Å is too large. Possible solutions are discussed in the text. Note, that the observed spectrum is oversampled although smoothed with a triangle of 64.8 ÅFWHM.

For the density and chemical structure we used model DD200c with T(r) based on light curve calculations corresponding to about 5 days before maximum

(Höflich et al. 1996). In Figure 5, the polarization spectrum for an oblate ellipsoid with an axis ratio of 0.89 is given which is seen at an inclination of 30° which fits best. Note that, quantitatively, the spectrum depends critically on the inclination. The depolarization in the ubiquitous metal lines has two main effects. Firstly, the mean polarization is about a factor of 2 to 3 smaller compared to that of a Thomson scattering atmosphere which provides a good approximation to Type II supernovae. Consequently, the same asphericity will produce much less polarization for an SN Ia compared to an SN II. Secondly, P varies strongly with wavelength on a typical scale of about the Doppler width. The variations with wavelength are significantly stronger than those in the flux spectra because it takes only one interaction to depolarize but many to thermalize a photon.

A comparison with the observations shows some qualitative similarity of the wavelength distribution of the features. The pattern in the models is mainly influenced by the atomic physics rather than the detailed explosion model. Therefore, the agreement or disagreement may be used to ask if the measurement can be regarded as a real detection. Most of the observed features have their equivalents in the theoretical model, although the predicted polarization above 6500 Å is much higher than observed (see below). The mean size of P implies an asphericity of ≈ 11 % at an inclination angle of 30°for the symmetry axis of the ejecta (Figure 5).

There are also some distinct shortcomings in the model polarization spectrum. The features corresponding to the products of partial burning (S II and Si II) are somewhat too strong compared to the observations. In principle, this may be compensated by slightly higher temperatures, small changes in the explosion model (e.g. a slightly larger Ni production) or, as test calculations have shown, by making the outer Si-rich layers almost spherical. A more severe problem is the spectrum above 6500 Å. Although the spectral features resemble the models, the absolute polarization is much lower. A component due to interstellar polarizaton (U=-0.1 %, Q = 0.25 %) helps to bring up P above 6500 % but completely destroys any reasonable fit at other wavelengths and, thus, does not solve the problem. This ISP is also inconsistent with broad-band data (see above). The increasing predicted polarization is insensitive to the details of the explosion models. It is caused primarily by the decreasing line blending towards longer wavelengths. Lower line blending also implies that the polarization in the red is produced at deeper layers (Höflich 1995b). Consequently, a possible solution to the problem is a nearly spherical, inner Ni region corresponding to expansion velocities $\approx 8000 \mathrm{km\,s^{-1}}$. This, together with the depolarization in Si and S, imply that asphericities must be mainly attributed to the distribution of chemical elements in the transition region between the Ni and Si layers (Höflich et al. 1996).

The correlation between flux and polarization spectra depends sensitively on the size of the line blanketing, thermalization parameter of lines and the actual wavelength. For a more detailed discussion see Höflich, Wheeler, & Wang (1997).

5. Discussions and Conclusions

SN 1996X is the first Type Ia supernova for which spectropolarimetry has suggested a polarized component intrinsic to the supernova. The peak to valley spectral variation in the Q and U spectra (Figure 4) is as high as 0.6% in many cases which, at an error level of 0.15%, gives a 4σ detection of the spectral features. The degree of the intrinsic polarization can be measured in terms of the deviation of the spectral features from the wavelength averaged degree of polarization. For SN 1996X, this is about 0.3%, which is small compared with the typical degree of polarization in SN 1987A and other Type II SNe (Wang et al. 1996). Previous observations of SN 1983N and SN 1992A have given only upper limits on the degree of polarization of Type Ia supernova (Spyromilio & Bailey, 1992; McCall et al. 1984). The SN 1996X observations were obtained prior to the optical maximum, and the detected polarization is most likely to be due to a distorted photosphere or element distribution. The correlation of features between the polarization spectra and flux spectra is not perfect in the entire observed wavelength range. This is expected because such a correlation depends sensitively on multiple scattering effects, the ratio between continuum and line optical depths, and thermalization in lines. The 2200 $\mathrm{km\,s^{-1}}$ blue shift of the features in the polarization spectrum relative to the flux spectrum (cf. Figure 3) can also be understood as due to multiple scattering. The model calculation shows that a strong feature in the polarization spectra does not require the presence of a strong feature in the flux spectra. Lines which hardly change the flux may produce significant depolarizations. The comparison with theo-

retical polarization spectra suggests an asphericity of about 11 % in the distribution of chemical elements. There are evidences that, the strong asphericity is limited to the transition region between nuclear statistical equillibrium (NSE) and partial burning. The distorted nature of the supernova envelope might arise from inhomogenous burning during the deflagration phase of the burning front (Khokhlov 1995).

Such a low degree of polarization probably does not seriously endanger the use of Type Ia as calibrated candles for distance indicators, but nonetheless poses a source of uncertainty. We will discuss these effects including the effects of inclination and the relation between flux and polarization spectra quantitatively in a separate study (Höflich, Wheeler, & Wang 1997).

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REFERENCES

Benetti, S., & Patat, F. 1996, IAUC, 6381

Brown, J. C., & McLean, I. S. 1977, A&A, 57, 141

Cropper, M., Bailey, J. A., McCowage, J., Cannon, R. D., Couch, W. J., Walsh, J. R., Strade, J. O., & Freeman F. 1988, MNRAS, 231, 695

Hill, G., & Trammell, S. R. 1996, in preparation

Höflich, P. 1987, in *ESO Workshop on the SN 1987A*, ed. I. J. Danziger (Garching:ESO), 387

Höflich, P. 1995a, ApJ, 440, 821

Höflich, P. 1995b, ApJ, 443, 89

Höflich, P., Dominik, C., Khokhlov, A., Nomoto, K., Thielemann, F. K., & Wheeler, J. C., 1995, in: Type Ia Supernovae, eds. R. Canal et al., Kluver, in press

Höflich, P., Wheeler J. C., Hines, D. C., and Trammell, S. R. 1996, ApJ, 459, 307

Höflich, P., Wheeler, J. C., & Wang, L. 1997, in preparation

Jeffery, D. J. 1991a, ApJ, 372, 264

Jeffery, D. J. 1991b, ApJS, 77, 405

Khokhlov, A. M. 1991, AA, 245, 114

Khokhlov, A. M. 1995, ApJ, 449, 695

Lee, T. A., Wamsteker, W., & Wisniewski, W. Z. 1972, ApJ, 177, L59

McCall, M. L., Reid, N., Bessell, M. S. and Wickramasinghe, D. 1984, MNRAS, 210, 839

Mendez, M., Clocchiatti, A., Benvenuto, O. G., Feinstein, C., & Marraco, H. G. 1988, ApJ, 334, 295

Miller, J. S., Robinson, L. B., & Goodrich, R. W. 1988, in Instrumentation for Ground-Based Astronomy, ed. L. B. Robinson (New York: Springer), p. 157

Serkowski, K. 1970, ApJ, 160, 1083

Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261

Shapiro, P. R., & Sutherland, P. G. 1982, ApJ, 263 902

Spyromilio, J., & Bailey, J. 1993, PASA, 10(3), 263

Suntzeff, N. B. 1996, IAUC, 6381

Trammell, S. R. 1994, Ph. D. Thesis, University of Texas

Wang, L., & Wheeler, J. C. 1996a, ApJ, 462, L27

Wang, L., & Wheeler, J. C. 1996b, IAUC, 6381

Wang, L., & Wheeler, J. C., Li, Z. W., & Clocchiatti, A. 1996, ApJ, 467, 435

Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249

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